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# PREDICTION OF PROPERTIES OF INTRAPLY HYBRID COMPOSITES

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## ABSTRACT

Equations based on the mixtures rule are presented for predicting the physical, thermal, hygral, and mechanical properties of unidirectional intraply hybrid composites (UIHC) from the corresponding properties of their constituent composites. Bounds were derived for uniaxial longitudinal strengths, tension, compression, and flexure of UIHC. The equations predict shear and flexural properties which agree with experimental data from UIHC. Use of these equations in a composites mechanics computer code predicted flexural moduli which agree with experimental data from various intraply hybrid angleplied laminates (IHAL). It is indicated, briefly, how these equations can be used in conjunction with composite mechanics and structural analysis during the analysis/design process.

## INTRODUCTION

The significance of fiber hybrid composites as an emerging structural material is extensively discussed in a recent state-of-the-art review (ref. 1). The various types of hybrid composites that have been used and their special advantages and disadvantages are covered in considerable detail in that review. The available methodology for analysis and design as well as areas that need further research are also covered. A need for equations for predicting the various properties of intraply hybrid composites based on the corresponding properties of their constituent composites was pointed out. The properties of interest include the following: physical, thermal, hygral, and mechanical. The objective of this paper is to present approximate equations which are based on the mixtures rule and also satisfy the conditions of mechanics for predicting all these properties. These equations can then be used in conjunction with composite mechanics computer codes for designing structural components made from intraply hybrid composites.

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The model and assumptions which justify the use of the method as well as the equations for predicting the various properties are described in detail. Comparisons with limited available experimental data are made to assess the adequacy of the method. It is indicated how these equations can be used in conjunction with available composite mechanics and structural analysis computer codes for the analysis/design of structural components made from intraply hybrid composites. The symbols used in the equations are defined when they appear and they are also summarized in appendix A for convenience.

### MODEL AND ASSUMPTIONS

The volume average (rule of mixtures) method for predicting approximately the various properties of unidirectional intraply hybrid composites (UIHC) is based on the model of a UIHC depicted schematically in figure 1. In this figure the model is represented by an array of parallelepiped cells which are differentiated by either empty or filled circles. The empty circles represent primary (majority) fibers or fiber bundles while the filled circles represent secondary (hybridizing) fibers or fiber bundles. Rectangular coordinate system axes (1, 2, 3) are defined where the 1-axis is parallel to the fiber direction, 2 is along the width (transverse direction) and 3 is through the thickness.

The assumptions required to apply the method of volume averages for predicting the various properties of UIHC are as follows:

- (1) Each parallelepiped cell is homogeneous and its properties are the same as those of either the primary fiber composite or the secondary fiber composite.
- (2) The cell boundaries are contiguous and there is a complete bond between cells.
- (3) The various properties of the constituent composites are known either by experiment or by use of composite micromechanics.
- (4) The UIHC and its constituent composites exhibit linear behavior in the regions of interest for this investigation.
- (5) Plane sections remain plane after deformation resulting from the application of uniform heat flux, moist environment, or stress on planes parallel to the coordinate planes (fig. 1).

A direct consequence of assumption (5) above is that the cells in the model (fig. 1) are connected in parallel in all three coordinate axes planes. For example, the stress in each cell due to a uniform stress in the 2-direction (transverse direction) is proportional to its stiffness. It is generally accepted that the rule of mixtures applies to properties along the fiber direction because along this direction the elements in the model are connected in parallel. However, the application of the rule of mixtures in the transverse and through the thickness

directions is not so obvious. As can be seen from figure 1, the elements in these directions are connected in both parallel and series. Another consequence from the above assumptions is that the UIHC is homogeneous as viewed from the outside. In view of the above discussion, the properties of UIHC can be approximately given by the rule of mixtures which can be expressed by the following general equation:

$$P_{HC} = P_{PC} + V_{SC}(P_{SC} - P_{PC}) \quad (1)$$

where  $P$  denotes the property of interest,  $V$  denotes hybridizing (secondary) composite volume ratio, subscript  $HC$  denotes hybrid composite property, subscript  $PC$  denotes primary composite property, and subscript  $SC$  denotes secondary composite property. Numerical subscripts denote direction. Extension of the equation for intraply hybrids from more than two different fibers is achieved by adding terms analogous to the second term in the right hand side of the equation (e.g., using superscripts the second term would be  $V_{SC}^{(2)}(P_{SC}^{(2)} - P_{PC})$ , etc.).

Equation (1) expresses each property of the UIHC as a linear combination of the corresponding properties of the constituent composites and satisfies both boundary conditions at  $V_{SC}$  equal "0" and 1. This equation, when applied to mechanical properties, satisfies the three conditions of mechanics (force equilibrium, compatibility, and stress-strain relationships). Typical properties of various unidirectional fiber composites which have been used to fabricate UIHC are summarized in Table I. Unidirectional composite properties which are not readily available and are usually predicted by using composite micromechanics are summarized in Table II.

### EQUATIONS FOR THE VARIOUS PROPERTIES

The properties of UIHC that may be required for structural and stress analyses of UIHC include physical, thermal, hygral, elastic, and strength and are summarized in appendix B. Selected equations are described below to clarify the notation used and to illustrate significant points. The desired equations are obtained by appropriate substitutions in equation (1). Constituent composite properties for use in the equations may be obtained from Tables I and II or can be determined from fiber and matrix properties using composite micromechanics (refs. 2 to 4). The various equations that may be needed for structural and stress analyses due to thermal hygral and mechanical loads are summarized in appendix B.

### Thermal, Hygral, and Elastic Properties

The heat conductivities of a UIHC are given by

$$K_{HCi} = K_{PCi} + V_{SC}(K_{SCi} - K_{PCi}) \quad (2)$$

where the subscript  $i$  is a generic index and denotes direction 1, 2, or 3 along which the heat conductivity is desired. The thermal expansion coefficients, moisture diffusivities, moisture expansion coefficients, normal moduli, and flexural moduli of UIHC are given by similar equations where  $K$  is replaced by the appropriate symbol for the desired property. The shear moduli of UIHC are given by

$$G_{HCij} = G_{PCij} + V_{SC}(G_{SCij} - G_{PCij}) \quad (3)$$

where the subscripts  $i$  and  $j$  denote planes 1-2, 2-3, or 1-3 in figure 1. The corresponding Poisson's ratios are given by

$$\nu_{HCij} = \nu_{PCij} + V_{SC}(\nu_{SCij} - \nu_{PCij}) \quad (4)$$

where the subscripts  $ij$  denote contraction in the  $j$  direction due to stress in the  $i$ -direction.

Unidirectional fiber composites (thoroughbreds) are generally assumed to be transversely isotropic, that is, the properties in the 3-direction are equal to corresponding properties in the 2-direction (fig. 1). For example:  $E_3 = E_2$ ;  $G_{13} = G_{12}$ ; and  $\nu_{13} = \nu_{12}$ . Properties associated with the 1-3 plane ( $G_{23}$  and  $\nu_{23}$ ) are not readily measured. Experimental value for these properties are virtually nonexistent. These properties are usually estimated by using composite micro-mechanics (ref. 2). As was already mentioned, the properties summarized in Table II were predicted by using the composite micromechanics available in the computer code (ref. 4).

### Strengths

The strengths (fracture stresses) ( $S$ ) of interest in performing stress analyses are: longitudinal tensile and compressive, transverse tensile and compressive, intralaminar (in-plane), interlaminar (short beam) and through-the-thickness shear; and longitudinal and transverse flexural (bending). The equations for predicting approximately the strengths of UIHC are obtained by appropriate substitutions in equation (1) as was the case for the properties already

described. Typical strengths which are readily measured, for constituent unidirectional composites are summarized in Table I. Those predicted by using composite micromechanics are summarized in Table II.

The longitudinal tensile strength of a UIHC is given by (refer to fig. 1)

$$S_{HC1T} = S_{PC1T} + V_{SC}(S_{SC1T} - S_{PC1T}) \quad (5)$$

where 1 denotes strength along the fiber direction and T denotes tension. The other normal strengths are obtained by substituting the appropriate subscripts in equation (5).

The intralaminar shear strengths are given by

$$S_{HC12} = S_{PC12} + V_{SC}(S_{SC12} - S_{PC12}) \quad (6)$$

$$S_{HC23} = S_{PC23} + V_{SC}(S_{SC23} - S_{PC23}) \quad (7)$$

where the subscripts 12 and 23 denote the shear planes (fig. 1). The interlaminar shear strength (short-beam-shear) of UIHC is given by

$$S_{HCSB} = S_{PCSB} + V_{SC}(S_{SCSB} - S_{PCSB}) \quad (8)$$

where the subscripts SB denote short-beam shear. The longitudinal flexural strength is given by

$$S_{HC1F} = S_{PC1F} + V_{SC}(S_{SC1F} - S_{PC1F}) \quad (9)$$

where the subscript F denotes flexural property. The transverse flexural strength is obtained by replacing subscript 1 by 2 in equation (9).

One important point need be made in connection with equations (5) to (9). As was already mentioned the equations show that the strength of the UIHC is a linear combination of the strengths of its constituent composites. Intraply hybrid composites which are of good quality, thoroughly mixed and completely bonded, should exhibit strengths which fall on or above the straight line described by the corresponding equation (full hybrid response).

Occasionally points will fall below the line. The causes for this are probably poor quality fabrication and/or a bad batch of material which results in ineffective use of the intraply hybrid.

### Lower Bounds on Longitudinal Strengths

Equations (5) and (9) will overestimate the longitudinal tensile ( $S_{HC1T}$ ), compressive ( $S_{HC1C}$ ) and flexural ( $S_{HC1F}$ ) strengths in UIHC with partial hybrid response (incomplete bond). Equations for predicting the lower bound strengths in such UIHC can be derived by assuming that the primary composite induces fracture at low values of the hybridizing ratio,  $V_{SC}$ , and that the secondary (hybridizing) composite induces fracture at high values of  $V_{SC}$ . The resulting equations are:

$$S_{HC1\gamma} = \frac{S_{PC1\gamma}}{E_{PC1}} E_{HC1} \quad \text{for } V_{SC} \leq V_T \quad (10)$$

$$S_{HC1\gamma} = V_{SC} S_{SC1\gamma} \quad \text{for } V_{SC} \geq V_T \quad (11)$$

where

$$V_T = \frac{1}{1 + \frac{S_{SC1\gamma}}{S_{PC1\gamma}} - \frac{E_{SC1}}{E_{PC1}}} \quad (12)$$

where  $\gamma$  denotes T, C, or F for tension, compression or flexure, respectively, and  $V_T$  denotes the hybridization ratio (volume ratio of secondary composite) at which transition of the fracture mode occurs. Implicit in the derivation of equations (10) to (12) is the assumption that the fracture strain of the fibers in the primary composite is smaller than that of the fibers in the secondary composite. If the reverse is true, then the role of the two composites in the equations should be interchanged. The graphical representation of equations (5), (9), (10), and (11) is shown in figure 2 for a graphite fiber/glass fiber intraply hybrid, HMS/S-G(901-S) (data from Table I). Partial hybrid response (incomplete bond or nonuniform mix) results in ineffective utilization of the intraply hybrid.

### Other Properties

Equations for predicting UIHC properties such as impact resistance, fatigue, and fracture toughness, can be derived by appropriate substitutions in equation (1). These equations, however, would only be applicable to initial damage where the intraply hybrid composite responds like a homogeneous material. Consequently, these equations will not account for cases in which a combination

of failure modes participates to propagate flaws. Therefore, equations for impact, fatigue, and fracture toughness are not given herein.

## COMPARISONS

Only limited experimental property data are available where the same composite system was used for both constituent composites and UIHC. Comparable data for thermal and hygral properties are not available. Comparisons between predictions and available experimental data are summarized in Table III for interlaminar shear strength (short beam shear), longitudinal flexural strength, and flexural modulus for three different intraply hybrids. The experimental data for these comparisons are from reference 5. The data for the relevant constituent composites is summarized in the top part of the table. The predictions were obtained by using equations (B8), (B18), and (B20). As can be seen the predicted values are within 12 percent of the interlaminar shear strength, 17 percent of the longitudinal flexural strength and 11 percent of the longitudinal flexural modulus. These results are considered very good for the following reasons:

1. The interlaminar shear and flexural responses are complex structural responses since they include combinations of tensile, compressive and shear stresses and strains.
2. The experimental data are evenly distributed above and below the theoretical predictions which is consistent with the observations made earlier with respect to complete and incomplete bonding.
3. The types of intraply hybrids investigated in reference 5 are the "tow-by-tow" variety. In these types of hybrids the hybridizing (secondary) fibers are not as uniformly dispersed as was assumed in the physical model.

The comparisons are also presented graphically in figure 3 together with the bounds for full and partial hybrid response. Note the interchange of the role between the primary and secondary composites for the AS/KEV UIHC. As can be seen in figure 3 the experimental points fall either between the bounds or above the full hybrid response bound. The largest percent difference between predicted and measured values (17 percent for the longitudinal flexural strength of the HMS/S-G intraply hybrid) is well above the partial hybrid response range which is about 30 percent relative to full hybrid response (fig. 3).

The important conclusion from these comparisons is that the rule-of-mixtures equations predict intraply hybrid mechanical properties which are in good agreement with measured data for hybridization volume percent up to about 30. An interesting observation from the data in Table III is that the intraply

hybrid AS/KEV shows an apparent synergistic effect since its flexural strength of 293 ksi is about 6 percent higher than that of its constituent composites, which is 275 ksi.

## APPLICATIONS TO DESIGN

The design of structural components made from angleplied intraply hybrid composites requires analyses which use composite macromechanics, laminate theory, and suitable failure criteria. Use of composite macromechanics, laminate theory and failure criteria involve lengthy tedious computations. These are generally done via composite mechanics computer codes. One such code is described in reference 4 as was already mentioned. The composite mechanics codes are used twice during one structural analysis and/or design iteration cycle. In the first step, they are used to generate the properties required for structural analysis such as axial and bending stiffnesses. In the second step, they are used to calculate the ply stresses and assess the laminate strength using the loads and/or the displacements determined from the structural analysis. Structural analyses to determine design variables such as displacements, forces, vibrations, buckling loads, and dynamic responses include application of corresponding special areas of structural mechanics for simple structural elements. General purpose finite element programs such as NASTRAN are used for the structural analysis of complex structural shapes, large structures made from simple structural elements, and structural parts made from combinations of simple elements such as bar, rods, and plates.

Composite mechanics codes require unidirectional composite (ply) properties as input. These properties for UIHC can be determined from the equations described previously. Once these properties are available the structural analysis and/or design of structural components made from intraply hybrids is the same as for "thoroughbred" composites. As an example, the equations were used to provide the required input to a computer code (ref. 4) to predict the flexural (bending) modulus for several intraply hybrid angleplied laminates (IHAL). The results obtained are compared to the experimental data in Table IV. As can be seen the predicted values are in reasonably good agreement with the measured data. This reasonably good agreement for the flexural moduli of IHAL is considered to be a further validation of the rule of mixtures method since the input to the code required four properties ( $E_{CH1}$ ,  $E_{CH2}$ ,  $G_{CH12}$ , and  $\nu_{CH12}$ ) predicted by four different equations for each UIHC. Aside from the validation aspect flexural moduli were calculated because they are important in determining structural responses (behavior variables) such as bending displacements, buckling

loads, vibration frequencies, and local deformations due to out-of-plane point or impact loads.

The previous discussion leads to the following conclusion and anticipation. The equations described herein predict mechanical properties at both the unidirectional composite and laminate levels which are reasonably good agreement with experimental data from three different intraply hybrid composite systems. Because of this good agreement, it is anticipated that these equations will apply equally well to other properties for these intraply hybrids and to properties for intraply hybrids from different constituent composite systems.

### SUMMARY

Equations were presented, based on the rule of mixtures, for predicting physical, thermal, hygral, and mechanical properties (including strength) of unidirectional intraply hybrid composites (UIHC). Results predicted by using these equations are in good agreement with limited available data for UIHC. Experimental strength data fell within or above bounds predicted by equations derived herein for this purpose. Use of these equations with a composite mechanics computer code, predicted flexural moduli of intraply angleplied laminates (IHAL) which were in reasonably good agreement with experimental data. The availability of these equations makes it possible to design, analyze, and optimize structural components from IHAL based on a large variety of available constituent composites.

### APPENDIX A - SYMBOLS

C	heat capacity
D	moisture diffusivity
E	normal (elastic) modulus
G	shear modulus
IHAL	intraply hybrid angleplied laminate
K	heat conductivity
P	property - physical, thermal, hygral, or mechanical
S	strength
UIHC	unidirectional intraply hybrid composite
V	volume (hybridization) ratio (volume of hybridizing (secondary) composite/total volume of intraply hybrid composite)

$V_T$	volume ratio at which transition of fracture modes occurs (eq. (12))
1, 2, 3	reference coordinate axis (fig. 1)
$\alpha$	thermal expansion coefficient
$\beta$	moisture expansion coefficient
$\nu$	Poisson's ratio
$\rho$	density

## Subscripts:

C	composite property, compression
F	fiber property, flexure
H	hybrid composite property
i	generic index (1, 2, or 3)
j	generic index (1, 2, or 3)
P	primary composite
S	secondary composite
SB	short beam (interlaminar) shear
T	tension, transition
1, 2, 3	direction associated with corresponding coordinate axis
$\gamma$	generic index (T, C, or F)

## APPENDIX B - LIST OF EQUATIONS

Several of the equations which are obtained by using the rule of mixtures (appropriate substitutions in eq. (1) in the text) and which may be used to predict various properties of intraply hybrid composites are summarized below. The notation is defined in appendix A.

Physical properties - fiber volume ratio and density:

$$V_{HCF} = V_{PCF} + V_{SC}(V_{SCF} - V_{PCF}) \quad (B1)$$

$$\rho_{HC} = \rho_{PC} + V_{SC}(\rho_{SC} - \rho_{PC}) \quad (B2)$$

Thermal properties - heat capacity, heat conductivities, and expansion coefficients:

$$C_{HC} = C_{PC} + V_{SC}(C_{SP} - C_{PC}) \quad (B3)$$

$$K_{HCi} = K_{PCi} + V_{SC}(K_{SCi} - K_{PCi}) \quad (B4)$$

$$\alpha_{HCi} = \alpha_{PCi} + V_{SC}(\alpha_{SCi} - \alpha_{PCi}) \quad (B5)$$

where  $i$  is a generic index and denotes direction 1, 2, or 3 along which the property is desired (fig. 1).

Hygral properties - moisture diffusivities and moisture expansion coefficients:

$$D_{HCi} = D_{PCi} + V_{SC}(D_{SCi} - D_{PCi}) \quad (B6)$$

$$\beta_{HCi} = \beta_{PCi} + V_{SC}(\beta_{SCi} - \beta_{PCi}) \quad (B7)$$

Elastic properties - normal and flexural moduli, shear moduli and Poisson's ratio:

$$E_{HCi} = E_{PCi} + V_{SC}(E_{SCi} - E_{PCi}) \quad i = 1, 2, 3 \quad (B8)$$

$$G_{HCij} = G_{PCij} + V_{SC}(G_{SCij} - G_{PCij}) \quad ij = 12, 23, 13 \quad (B9)$$

$$\nu_{HCij} = \nu_{PCij} + V_{SC}(\nu_{PCij} - \nu_{PCij}) \quad ij = 12, 23, 13 \quad (B10)$$

$$E_{HCiF} = E_{PCiF} + V_{SC}(E_{SCiF} - E_{PCiF}) \quad i = 1, 2 \quad (B11)$$

Strengths - longitudinal tension and compression, and transverse tension and compression:

$$S_{HC1T} = S_{PC1T} + V_{SC}(S_{SC1T} - S_{PC1T}) \quad (B12)$$

$$S_{HC1C} = S_{PC1C} + V_{SC}(S_{SC1C} - S_{PC1C}) \quad (B13)$$

$$S_{HC2T} = S_{PC2T} + V_{SC}(S_{SC2T} - S_{PC2T}) \quad (B14)$$

$$S_{HC2C} = S_{PC2C} + V_{SC}(S_{SC2C} - S_{PC2C}) \quad (B15)$$

Strengths - intralaminar (in-plane) shear and through-the-thickness shear:

$$S_{HC12} = S_{PC12} + V_{SC}(S_{SC12} - S_{PC12}) \quad (B16)$$

$$S_{HC23} = S_{PC23} + V_{SC}(S_{SC23} - S_{PC23}) \quad (B17)$$

Strengths - flexural and interlaminar shear (short-beam-shear):

$$S_{HC1F} = S_{PC1F} + V_{SC}(S_{SC1F} - S_{PC1F}) \quad (B18)$$

$$S_{HC2F} = S_{PC2F} + V_{SC}(S_{SC2F} - S_{PC2F}) \quad (B19)$$

$$S_{HCSB} = S_{PCSB} + V_{SC}(S_{SCSB} - S_{PCSB}) \quad (B20)$$

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TABLE I. - UNIDIRECTIONAL COMPOSITE PROPERTIES: TYPICAL ROOM TEMPERATURE VALUES<sup>a</sup>

Material	Epoxy matrix resin	Form	Fiber volume ratio	Density		Longitudinal (0°) properties				Transverse (90°) tension		Flexural properties		Interlaminar (short beam) shear strength, ksi	In-plane (intralaminar) shear properties		Poisson's ratio	Ply thickness, mils
				g/cm <sup>3</sup>	lb/in <sup>3</sup>	Tension		Compression		Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi		Strength, ksi	Modulus, msi		
						Strength, ksi	Modulus, msi	Strength, ksi	Modulus, msi									
Boron	5505	Tape	0.50	1.99	0.072	230	30	360	32	9.1	2.7	---	16.0	19.0	0.93	0.21	5.2	
Graphite:																		
AS	3501		.60	1.54	.055	210	18.5	170	16	9.0	1.3	225	17	8.7	.83	.25	5-8	
HMS	934			1.63	.059	120	30	90	25	12.5	2.0	150	28	10.5	.85	.20	7-8	
HTS	5208			1.55	.056	215	25	155	24	13	1.3	245	23	10.5	.85	.21	7-8	
T-300	5208			---	---	210	20	210	20	6.5	1.5	260	20	14	.90	.21	5-7	
GY-70	934			1.69	.061	85	40	75	38	6.0	1.2	135	38	7.5	.60	.25	6-8	
Mod-I	5208			1.67	.060	120	31	100	29	12.0	2.0	186	29	10	.85	.22	6-8	
Mod-II	5208			1.54	.050	186	24	100	23	9.7	1.9	210	23	14.9	.72	.38	6-8	
KEV:																		
(Kevlar-49)	----			1.38	.050	200	11.0	40	11	4.1	.8	90	11	7.0	.3	.34	5-7	
(Kevlar-29)	----			1.38	.050	200	5.0	40	5.0	4.1	.7	90	5.0	6.0	.3	.34	5-7	
Nomex	----			----	----	----	----	----	----	----	----	----	----	----	----	----	----	
Glass:																		
E	1002			1.80	.065	160	5.7	90	4.6	b <sub>14</sub>	b <sub>7</sub>	165	5.3	10.0	b <sub>7</sub>	b <sub>3</sub>	10	
S-G(901-S)	1002S			1.82	.066	219	6.3	120	6.0	-----	----	200	6.0	11.2	-----	----	10	
S2-S	1002S			1.82	.066	180	6.3	110	6.0	-----	----	170	6.0	10.5	-----	----	10	

<sup>a</sup> From ref. 2.<sup>b</sup> Average values.

TABLE II. - UNIDIRECTIONAL COMPOSITE PROPERTIES PREDICTED BY COMPOSITE MICROMECHANICS

USING THE COMPUTER CODE REF. 4

	Boron	Mod-I	Mod-II	T300	T75	Kevlar-49 (KEV)	S-glass (S-G)	E-glass (E-G)
Heat capacity, Btu/(lb/°F)	0.29	0.20	0.20	0.2	0.2	0.21	0.19	0.19
Heat conductivity ( $K_1$ ), Btu/(hr)(ft <sup>2</sup> )(°F/in)	12.0	291	291	348	291	4.6	4.6	4.5
Heat conductivity ( $K_2$ , $K_3$ ), Btu/(hr)(ft <sup>2</sup> )(°F/in)	4.0	3.7	3.7	5.2	3.7	2.7	2.7	2.5
Thermal expansion coefficient ( $\alpha_1$ ), 10 <sup>-6</sup> in/in/°F	3.1	-0.2	0.01	0.5	-0.2	-1.4	3.9	4.1
Thermal expansion coefficient ( $\alpha_2$ , $\alpha_3$ ), 10 <sup>-6</sup> in/in/°F	16.3	23.2	23.2	16.2	23.4	32.2	16.1	16.0
Shear modulus ( $G_{23}$ ), 10 <sup>6</sup> psi	0.58	0.30	0.33	0.37	0.34	0.24	0.50	0.49
Poisson's ratio ( $\nu_{23}$ )	0.53	0.40	0.41	0.47	0.41	0.42	0.50	0.49
Through-the-thickness shear strength ( $S_{23}$ ), ksi	13.2	6.0	7.7	8.5	8.2	8.3	8.2	6.1

Note: Subscript 1 denotes property along the fiber direction.

Subscript 2 denotes property transverse to the fiber direction.

Subscript 3 denotes property through the thickness.

Double subscripts denote properties in that plane, see also fig. 1.

TABLE III. - COMPARISONS OF EXPERIMENTAL AND PREDICTED PROPERTIES

[Experimental data from ref. 5.]

Constituent composites		Short-beam-shear strength, ksi			Flexural strength, ksi			Flexural modulus, $10^6$ psi		
					Experi- mental	Pre- dicted	Differ- ence, %	Experi- mental	Pre- dicted	Differ- ence, %
AS		18	--	--	275	---	---	18	--	---
HMS		7	--	--	172	---	---	28	--	---
S-G		16	--	--	275	---	---	8	--	---
KEV		6	--	--	98	---	---	11	--	---
Intraply hybrids										
Hybrid	Constituents, %									
HMS/S-G	73.5/26.5	8	9	12	171	200	17	21	23	10
AS/S-G	75.0/25.0	18	18	0	271	275	1	18	16	-11
AS/KEV	87.5/12.5	15	16	7	293	253	-14	18	17	-6

<sup>a</sup>Predictions based on full hybrid response.TABLE IV. - INTRAPLY HYBRID COMPOSITE FLEXURAL MODULUS ( $10^6$  psi)

COMPARISON BETWEEN MEASURED AND PREDICTED DATA

Ply configuration	AS/S-G		AS/KEV		HMS/S-G	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
( $\pm 40, 0, 10, 0, -10$ ) <sub>S</sub>	7.75	7.04	7.95	7.33	6.81	8.89
( $\pm 22, 0, 22, 0, -22$ ) <sub>S</sub>	12.3	11.49	12.35	12.43	12.71	14.30
( $\pm 45, 0, 45, 0, -45$ ) <sub>S</sub>	5.19	5.29	4.4	5.38	6.78	6.71
Fiber composition	75/25		90/10		62/38	

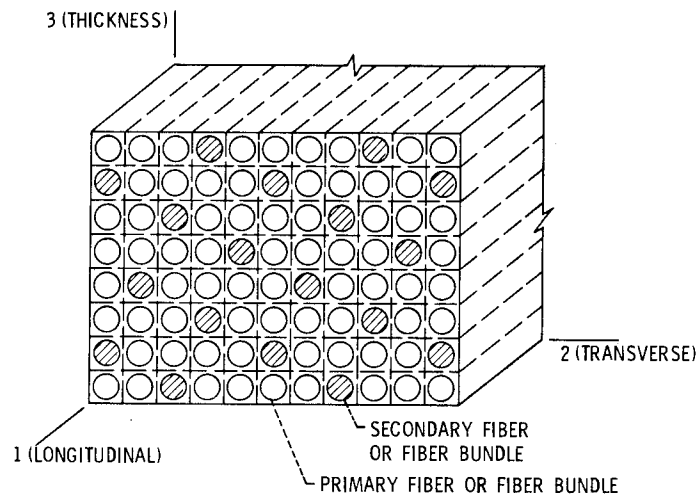


Figure 1. - Unidirectional intraply hybrid composite schematic.

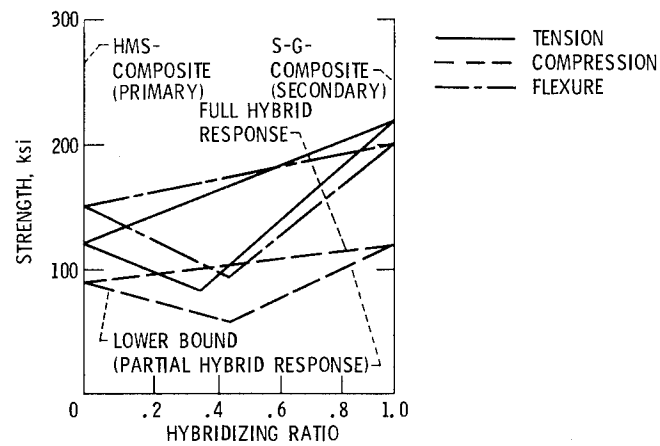


Figure 2. - Effects of partial hybrid response on the longitudinal strengths of unidirectional intraply hybrid composites (HMS/S-G (901-S)).

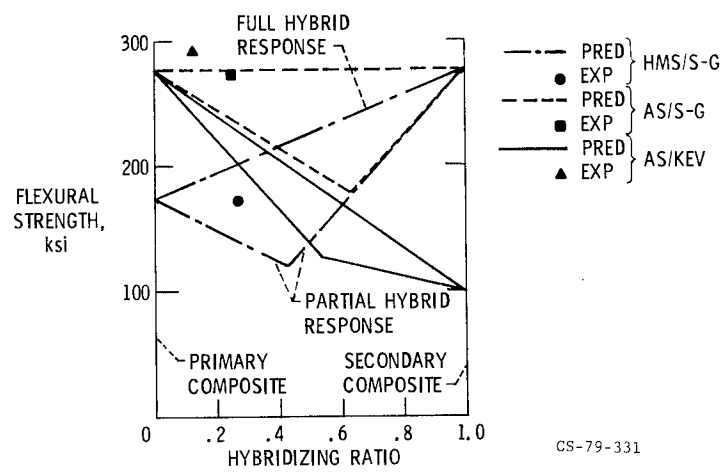


Figure 3. - Comparison of predicted and experimental results for flexural strength (experimental data from table III).

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16. Abstract <p>Equations based on the mixtures rule are presented for predicting the physical, thermal, hygral, and mechanical properties of unidirectional intraply hybrid composites (UIHC) from the corresponding properties of their constituent composites. Bounds were derived for uniaxial longitudinal strengths, tension, compression, and flexure of UIHC. The equations predict shear and flexural properties which agree with experimental data from UIHC. Use of these equations in a composites mechanics computer code predicted flexural moduli which agree with experimental data from various intraply hybrid angleplied laminates (IHAL). It is indicated, briefly, how these equations can be used in conjunction with composite mechanics and structural analysis during the analysis/design process.</p>			
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